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RESEARCH MEMORANDUM

EFFECT OF COMBUSTION-CHAMBER PRESSURE AND NOZZLE EXPANSION RATIO ON THEORETICAL PERFORMANCE OF SEVERAL ROCKET PROPELLANT SYSTEMS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF COMBUSTION-CHAMBER PRESSURE AND NOZZLE EXPANSION RATIO ON THEORETICAL PERFORMANCE OF SEVERAL ROCKET PROPELLANT SYSTEMS

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SUMMARY

A brief series of calculations was made for several rocket propellant systems to determine the separate effects of increasing the combustion-chamber pressure and the nozzle expansion ratio on the specific impulse. The propellant combinations were hydrogen-fluorine, hydrogen-oxygen, ammonia-fluorine, AN-F-58 fuel-white fuming nitric acid (95 percent). The results indicate that an increase in specific impulse obtainable with an increase in combustion-chamber pressure is almost entirely caused by the increased expansion ratio through the nozzle.

INTRODUCTION

In the search for ways to improve the performance of rockets, the possibility of using combustion-chamber pressures greater than the conventional 300 pounds per square inch is being considered. Performance calculations for several propellant systems are presented in references 1 to 4 for combustion-chamber pressures as high as 3000 pounds per square inch. In all cases, increases in specific impulse of approximately 21 to 25 percent were obtained with an increase in pressure to 3000 pounds per square inch.

In order to obtain a better concept of the separate effects of combustion pressure and expansion ratio, a brief series of calculations was made at the Lewis laboratory of the NACA for the following propellant systems

(a) Ammonia, NH_3 - fluorine, F_2.

(b) Hydrogen, H_2 - fluorine, F_2

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(c) Hydrogen, H_2 - oxygen, O_2

(d) AN-F-58 fuel - white fuming nitric acid, HNO_3, (95 percent), WFNA

Specific impulse values for different mixture ratios of system (a) were determined at combustion-chamber pressures of 300, 1000, and 2000 pounds per square inch with an exit pressure of 1 atmosphere.

As the maximum increase in performance of system (a) was obtained at the stoichiometric mixture, values of specific impulse were calculated for only the stoichiometric mixtures of systems (b), (c), and (d). These values, determined for an exit pressure of 1 atmosphere, were compared with a series in which the exit pressure was varied such that a constant expansion ratio of 136.1 was maintained. The comparison yielded an indication of the separate effects of combustion-chamber pressure and expansion ratio.

METHOD OF CALCULATIONS

The calculations described herein were based on the assumptions,

(1) Adiabatic combustion

(2) Isentropic expansion

(3) Chemical equilibrium among the products of combustion through the processes

All products of reaction were considered to be in the ideal gas state and included the following chemical species for the appropriate reactions: water vapor, H_2O; hydroxyl radical, OH; hydrogen, H_2; oxygen, O_2; atomic oxygen, O; atomic hydrogen, H; hydrogen fluoride, HF; fluorine, F_2; atomic fluorine, F; carbon dioxide, CO_2; carbon monoxide, CO; nitrogen, N_2; nitrogen oxide, NO; and atomic nitrogen, N.

The specific impulse, $I\left(\frac{\text{lb-sec}}{\text{lb}}\right)$, was calculated from the difference in heat content of the products of reaction in the combustion chamber with that at the nozzle exit according to the equation

$$I = 9.328 \sqrt{\left[\frac{\sum_i n_i \left(H_T^0\right)_i}{\sum_i n_i M_i}\right]_c - \left[\frac{\sum_i n_i \left(H_T^0\right)_i}{\sum_i n_i M_i}\right]_e}$$

where

n_i moles of product i

$(H_T^o)_i$ enthalpy of product i

M_i molecular weight of product i

The subscripts c and e indicate combustion and exit conditions, respectively. The method used in determining the combustion chamber and exit temperatures and composition of the products is reported in reference (5).

The values of thrust coefficient C_F were determined from the defining equation

$$C_F = \frac{I}{\left(\frac{a}{w}\right)_t P_c}$$

where

$(a/w)_t$ area of nozzle throat per unit weight flow of propellant, (sq in./(lb)/(sec))

P_c combustion pressure, (lb/sq in. absolute)

The area of the nozzle throat was determined with the assumptions of no heat loss and chemical equilibrium maintained among the products of reaction by a method developed at the Lewis laboratory.

The characteristic velocity C^* is defined as

$$C^* = \frac{Ig}{C_F}$$

where g is the gravitational constant.

THERMOCHEMICAL DATA

The values of enthalpy, entropy, and specific heat for all products of reaction except HF, F_2, and F were taken from reference 6; those for HF and F_2 were calculated from spectroscopic data of reference 7; and those for F were calculated from the spectroscopic data of reference 8.

The values of the heat of formation of all the products of reaction except F and of all the propellants except AN-F-58 fuel were taken from reference 6. The heat of formation of F at 0° K used in this calculation (17.8 Kcal/mole) was received in a personal communication from Dr. F. D. Rossini of the National Bureau of Standards. The values of 18,640 Btu per pound and 0.163, determined at the Lewis laboratory from an analysis of a typical sample of AN-F-58 fuel, were used as the heat of combustion and H/C ratio, respectively. 1283

The physical and chemical properties of the propellants are listed in table I. The propellants were taken as liquids at the following initial tank temperatures:

Propellant	Initial temperature (°K)
Ammonia	239.76
Hydrogen	20.39
Oxygen	90.19
Fluorine	85.24
AN-F-58 fuel	298.16
White fuming nitric acid (95 percent)	298.16

RESULTS AND DISCUSSION

The effect of increasing combustion-chamber pressure on the performance of the ammonia-fluorine propellant system is shown in figure 1 for various mixture ratios and expansion to one atmosphere. The calculated performance points are listed in table II. For each mixture ratio the specific impulse increased as the pressure increased from 300 to 2000 pounds per square inch absolute. The increase was greatest at the stoichiometric point (23.01 fuel percent by weight) and decreased for both fuel and oxidant rich mixtures.

Mixture ratio (percent fuel by weight)	Increase in specific impulse (percent)
18.31	16
23.01	21
24.74	20
30.95	18

1283

The increase in the performance obtained with increasing combustion-chamber pressures for stoichiometric mixtures of the propellant systems hydrogen-fluorine, hydrogen-oxygen, and AN-F-58 fuel-white fuming nitric acid (95 percent) is shown in figures 2, 3, and 4, respectively, and the calculated points are tabulated in table III. The values of specific impulse for the three values of expansion ratio and chamber pressure at stoichiometric mixture are:

Expansion ratio	Combustion-chamber pressure (lb/sq in. abs)	Specific impulse (lb-sec/lb)			
		H_2-F_2	H_2-O_2	AN-F-58 - WFNA	NH_3-F_2
20.4	300	341.4	312.5	223.6	311.0
68.0	1000	396.1	363.2	257.3	357.4
136.1	2000	421.4	387.0	272.6	377.3

The stoichiometric point calculated for the ammonia-fluorine system was included in this table for comparison. The percentage increase in specific impulse was approximately the same for all these systems and averaged about 23 percent. However, when a constant expansion ratio of 136.1 was assumed, the performance increase for each of these three propellant systems became practically negligible as shown in the following table:

Propellant system	Increase in specific impulse for chamber pressure increased 300 to 2000 lbs/sq in. (percent)	
	P_c/P_e variable, $P_e = 1$	$P_c/P_e = 136.1$, P_e variable
H_2-F_2	23	2.1
H_2-O_2	24	1.6
An-F-58-WFNA	22	0.7

These results indicate that an increase in specific impulse obtainable with an increase in combustion-chamber pressure is almost entirely caused by the increased expansion ratio through the nozzle. At sea level this increase can be obtained only by increasing the chamber pressure. At present, combustion-chamber pressures greater than 1000 pounds per square inch are improbable and hence the upper limit on expansion ratio at sea level is about 68.0. With this expansion ratio, the specific impulse of the hydrogen-oxygen propellant system at stoichiometric will be about 16 percent greater than that at an expansion ratio of 20.4. This increase in chamber pressure, however, would greatly increase the engine weight and pumping requirements.

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At altitude the low ambient pressures make possible high expansion ratios at moderate values of combustion-chamber pressure. For example, a rocket designed to operate at 45,000 feet with a combustion-chamber pressure of 300 pounds per square inch would have an expansion ratio of approximately 136.1 and would develop 1283
24 percent greater specific impulse than a rocket designed for sea level flight with the same combustion-chamber pressure. Moreover, experiments show (references 9 and 10) that an engine designed for complete expansion at altitude will not have as large a loss from overexpansion at sea level as simple theory predicts. In other words, it appears more desirable to increase the performance of a rocket that is to operate at high altitude by increasing the expansion ratio rather than by increasing the chamber pressure. It should be recognized that increasing the nozzle exit area to increase expansion ratio may add external drag and will increase the cooling requirements.

SUMMARY OF RESULTS

The results of a brief series of calculations made to determine the separate effects of increasing chamber pressure and expansion ratio on the specific impulse of rocket engines are as follows:

1. The values of specific impulse, for three values of expansion ratio and chamber pressure at stoichiometric mixture are:

Expansion ratio	Combustion-chamber pressure (lb/sq in. abs)	Specific impulse (lb-sec/lb)			
		H_2-F_2	H_2-O_2	NH_3-F_2	AN-F-58-WFNA
20.4	300	341.4	312.5	311.0	223.6
68.0	1000	396.1	363.2	357.4	257.3
136.1	2000	421.4	387.0	377.3	272.6

2. For the systems hydrogen-fluorine, hydrogen-oxygen, and AN-F-58 fuel - white fuming nitric acid at a constant expansion ratio with stoichiometric mixtures, an increase in chamber pressure from 300 to 2000 pounds per square inch absolute increased the specific impulse on the order of 1 to 2 percent.

3. The performance of the ammonia-fluorine system at several mixture ratios showed the maximum gain in specific impulse from a

simultaneous increase in combustion chamber pressure and expansion ratio occurred at the stoichiometric mixture.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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TABLE I - PHYSICAL AND CHEMICAL PROPERTIES OF PROPELLANTS

[Temperatures in superscripts, °C]

Propellants	Molecular weight (g/mole)	Density (g/cc)	Enthalpy of formation (kcal/mole)	Enthalpy of vaporization (kcal/mole)	Boiling point (°C)	Freezing point (°C)
Hydrogen	2.016	$0.070^{-252.77}$	(gas) 0^{25}	$0.216^{-252.8}$	-252.77	-259.20
Oxygen	32	1.14^{-183}	(gas) 0^{25}	$1.6299^{-182.97}$	-182.97	-218.77
Fluorine	38	1.108^{-187}	(gas) 0^{25}	$1.51^{-187.92}$	-187.92	-217.96
White fuming nitric acid (100%)	63.016	1.513^{20}	(liq) -41.404^{25}	9.43^{20}	20	-41.59
AN-F-58	122±5%	$0.765^{15.7}$	(a)-1260^{25}	-------------	-------	-42±3°
Ammonia	17.032	0.817^{-79}	(gas) -11.04^{25}	$5.581^{-33.4}$	-33.4	-77.74

[a]Heat of combustion.

TABLE II - PERFORMANCE OF AMMONIA-FLUORINE PROPELLANT SYSTEM

Fuel mixture ratio (percent by weight)	Combustion chamber pressure, P_c (lb/sq in. abs.)	Specific impulse I (lb-sec/lb)	Combustion chamber temperature, T_c (°K)	Mean molecular weight in combustion chamber M_c (gram/mole)	Exit nozzle temperature T_e (°K)	Mean molecular weight at exit nozzle, M_e (gram/mole)
18.31	300	288.3	4209.6	20.093	2265.0	20.675
	1000	321.0	4385.7	20.288	1637.7	20.704
	2000	334.5	4474.6	20.389	1391.7	20.888
[a]23.01	300	311.0	4394.9	19.100	3112.0	20.717
	1000	357.4	4528.2	19.369	2564.8	21.109
	2000	377.3	4664.6	19.529	2179.7	21.147
24.74	300	311.6	4244.0	18.694	2974.0	20.155
	1000	355.8	4468.1	18.961	2366.3	20.441
	2000	374.6	4598.2	19.117	1996.1	20.466
30.95	300	303.2	3870.0	17.324	2423.7	18.278
	1000	342.4	4038.6	17.541	1828.2	18.343
	2000	358.7	4130.4	17.660	1528.3	18.344

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[a]Stoichiometric.

TABLE III - CALCULATED PERFORMANCE PARAMETERS AT VARIOUS PRESSURES

Combustion chamber pressure P_c (lb/sq in. abs.)	Combustion chamber temperature T_c (°K)	Mean molecular weight in combustion chamber M_c (gram/mole)	Expansion to 1 atmosphere					Expansion to P_c/P_e = 136.1		
			Specific impulse I (lb-sec/lb)	Exit nozzle temperature T_e (°K)	Mean molecular weight at nozzle exit M_e (gram/mole)	Thrust coefficient C_F	Characteristic velocity c^* (ft/sec)	Specific impulse I (lb-sec/lb)	Exit nozzle temperature T_e (°K)	Mean molecular weight at nozzle exit M_e (gram/mole)
$H_2 + F_2$										
300	4575.2	16.946	341.4	3456.2	18.742	1.426	7704	412.9	2843.0	19.628
1000	4867.3	17.244	396.1	3127.3	19.548	1.626	7838	418.5	2851.5	19.784
2000	5044.9	17.428	421.4	2844.1	19.849	1.712	7918	←	←	←
$H_2 + O_2$										
300	3446.4	15.700	312.5	2696.1	16.913	1.436	7001	381.0	2289.3	17.528
1000	3618.6	15.963	363.2	2482.9	17.486	1.646	7098	384.9	2316.8	17.666
2000	3719.2	16.120	387.0	2327.8	17.726	1.733	7186	←	←	←
AN-F-58 + HNO_3 (95 percent)										
300	2930.3	25.937	223.6	2176.8	27.147	1.434	5019	270.7	1688.7	27.437
1000	3022.0	26.163	257.3	1864.3	27.409	1.633	5068	271.9	1675.3	27.452
2000	3072.9	26.289	272.6	1669.0	27.469	1.723	5092	←	←	←

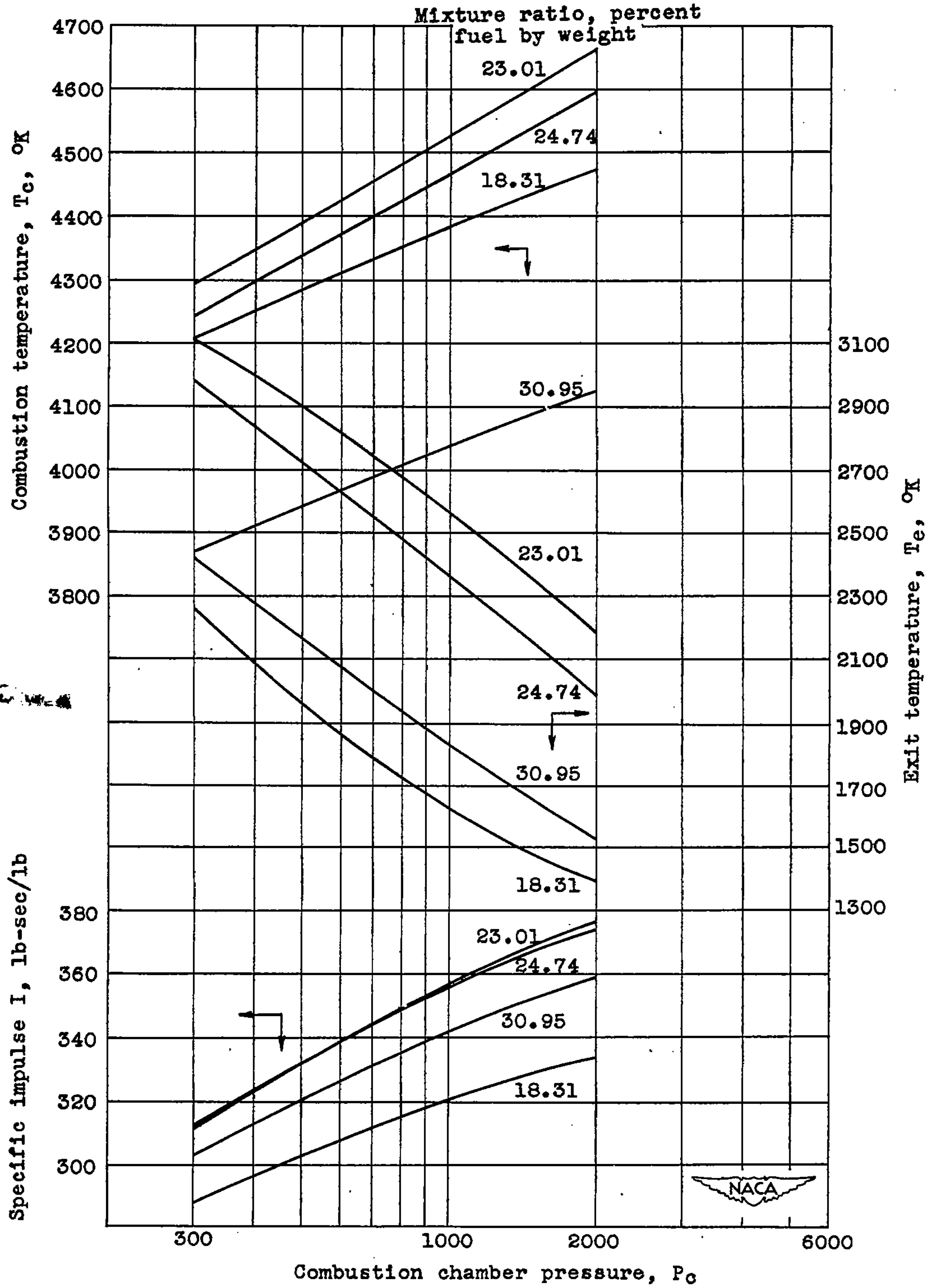

Figure 1. - Effect of combustion pressure and expansion ratio on performance of ammonia-fluorine propellant system at several mixture ratios.

1283

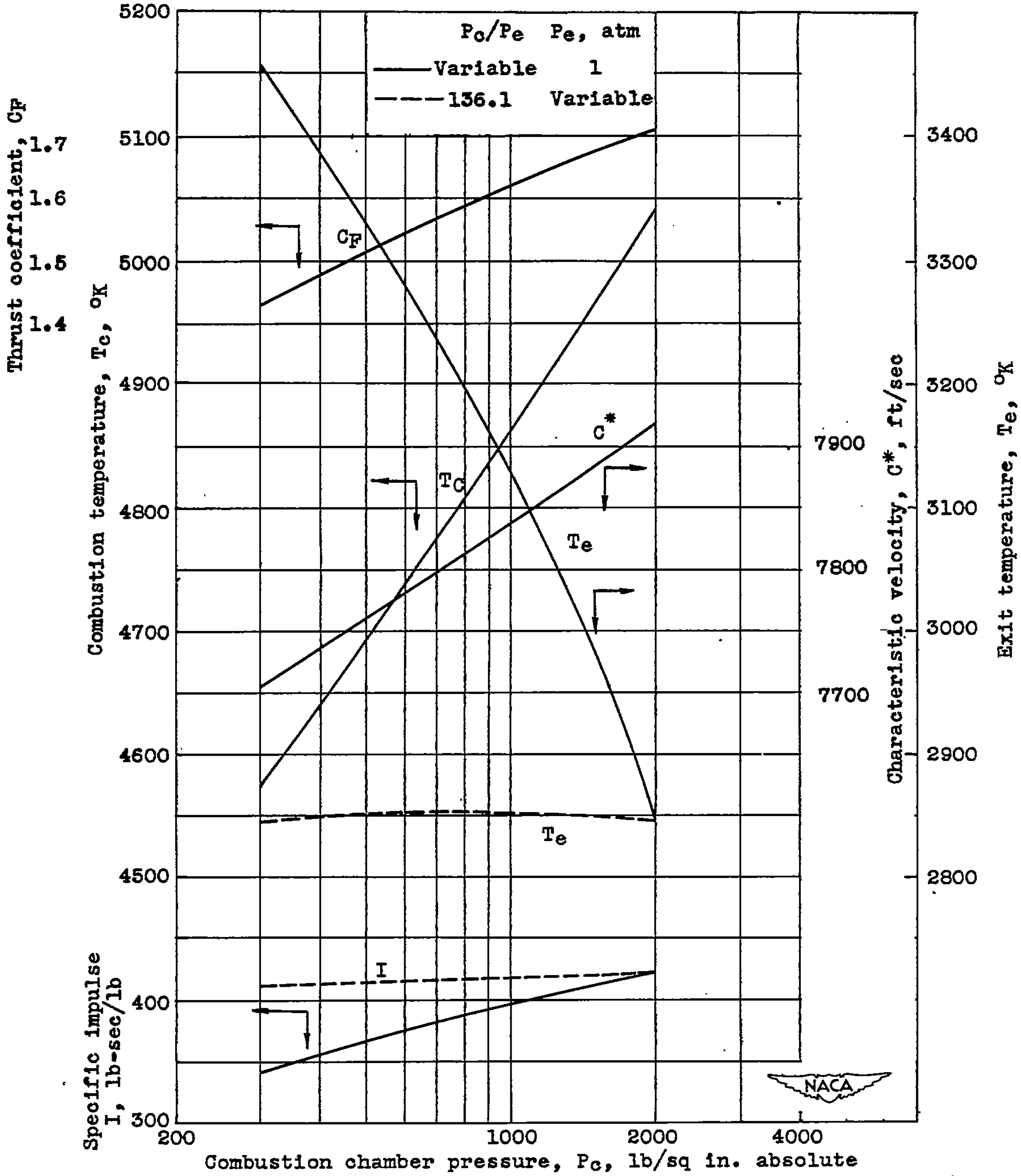

Figure 2. - Effect of combustion pressure and expansion ratio on performance of hydrogen and fluorine at stoichiometric mixture ratio.

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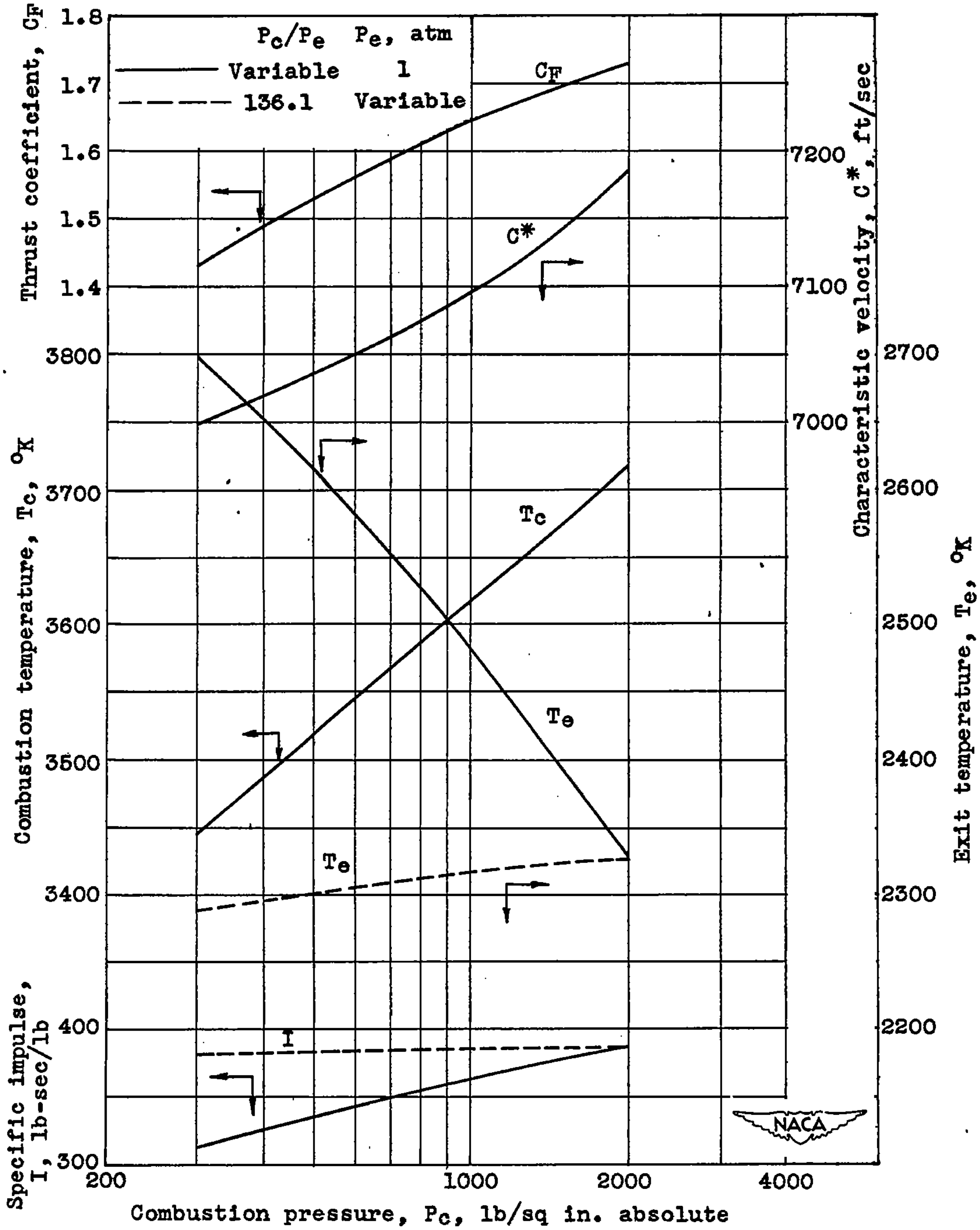

Figure 3. - Effect of combustion pressure and expansion ratio on performance of hydrogen and oxygen at stoichiometric mixture ratio.

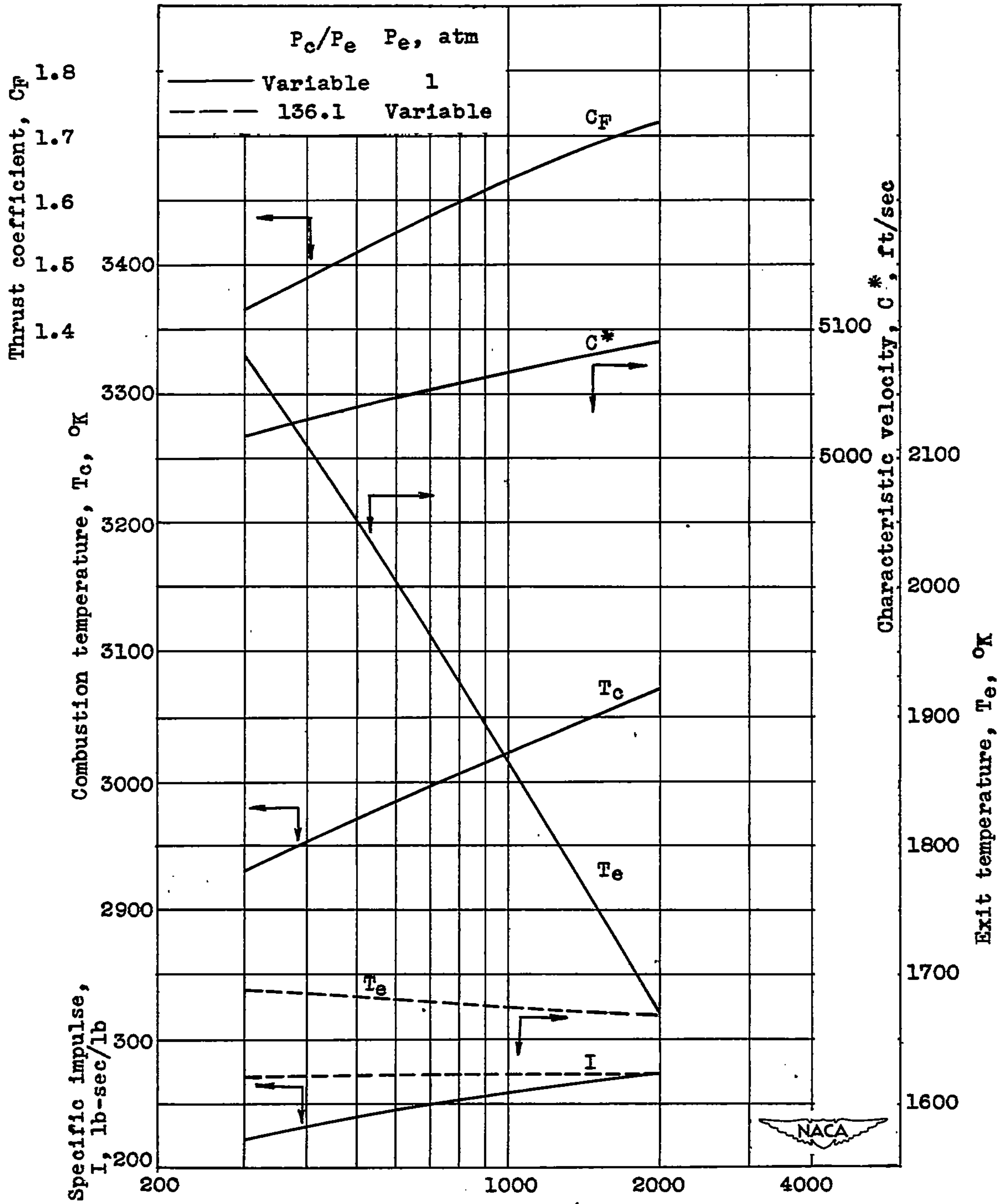

Figure 4. - Effect of combustion pressure and expansion ratio on performance of AN-F-58 gasoline and 95-percent nitric acid at stoichiometric mixture ratio.

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